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Science & Technology REVIEW

December 1996

Lawrence
Livermore
National
Laboratory

Crossing the Petawatt Threshold

Also in this issue:

- **Stockpile Surveillance**
- **Earth Core Studies**
- **3-D Computer Motion Modeling**

About the Cover

Adjusting a diagnostic lens in Lawrence Livermore's new ultrashort-pulse laser, called the Petawatt, is laser physicist Deanna Pennington. World-record peak power of 1.25 petawatts (1.25 quadrillion watts) was reached May 23, 1996. In this issue beginning on p. 4, we discuss the challenges and development of this extraordinary laser.

Cover photo: Bryan L. Quintard

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About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy. At Livermore, we focus science and technology on assuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published ten times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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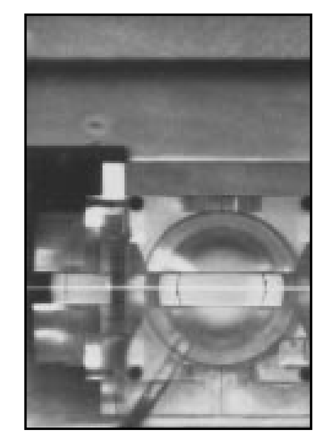

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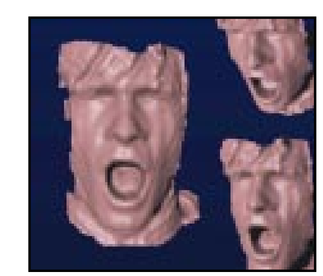

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Director looks at Lab's technical challenges

Describing himself as very optimistic about Lawrence Livermore's progress and future, Director Bruce Tarter says that in the coming year, the Laboratory will "have to deliver on major products" in addition to "first rate R&D" in the areas of national security, energy, and biotechnology.

With the country committed to no nuclear testing under the Comprehensive Test Ban Treaty, Lawrence Livermore must "focus on providing Congress and the President with high confidence in the stockpile," the Director said. "This means an enhanced effort on surveillance and life extension of the current stockpile and rapid progress on major initiatives." He stressed that the National Ignition Facility (NIF) must remain on schedule and within costs and that the Accelerated Strategic Computing Initiative (ASCI) must be a "fast-track program." NIF and ASCI are two key components of the effort to ensure the integrity of the nation's nuclear weapons stockpile without nuclear testing.

Tarter said the Laboratory's challenge in energy is proving, with the U.S. Enrichment Corp. (USEC), that "laser isotope separation can work in the commercial environment." USEC has designated the Lab's isotope separation technology as the way to make reactor fuel in the 21st century (see AVLIS news item next column).

In biotechnology, Tarter said, stronger production capability will be needed to sequence the human genome. Explained the Director: "For the last half dozen years, we have been mapping with markers to lay out the structure of the genome; now we have to sequence it, that is, fill in all the details—a much more production-oriented activity that is driven by national and international competition."

Tarter outlined the challenges facing the Laboratory in the coming year in an address to employees in early October. Discussing the budget for FY 1997, Tarter said the Lab's total costs will be $1,057 million, with $929 million going to operating costs and the remainder to construction and major capital procurements.

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Reis dedicates ASCI–Blue Pacific

Mission, partnership, and technology were the themes as Vic Reis, the DOE's assistant secretary for Defense Programs, visited the Laboratory in late October. At Livermore, he dedicated ACSI–Blue Pacific, the 3-trillion-calculations-per-second supercomputer being built as part of the DOE's Accelerated Strategic Computing Initiative (ASCI).

Targeted for demonstration in December 1998, the supercomputer is a collaboration between Livermore and IBM in which, said Reis, "both partners bring unusual talent."

"The deterrence mission remains the underpinning of our national security," Reis noted, and the ASCI supercomputer will be a "central tool" in efforts to keep the nation's stockpiled nuclear weapons safe and reliable.

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AVLIS team puts enrichment technology through its paces

The Laboratory's Atomic Vapor Laser Isotope Separation (AVLIS) team has a new goal: extend operating hours for the Livermore-developed uranium enrichment technology, demonstrating the reliability required of a fully functioning enrichment plant by the end of the calendar year. Achieving that goal means around-the-clock, seven-day-a-week operation of the key AVLIS Demonstration Facility areas: lasers, separators, and control devices.

AVLIS personnel have been running ever-lengthening endurance tests at Livermore for the U.S. Enrichment Corp. (USEC). These design verification runs are aimed at bringing the technology to the point where USEC can use it for commercial production of enriched uranium.

USEC, a U.S. government corporation in the process of privatizing, produces and markets uranium enrichment services worldwide. It selected Lawrence Livermore-developed AVLIS enrichment technology as the "technology of choice" to ensure that the U.S. maintains its lead in the world uranium enrichment market.

In a 200-hour test in September, the AVLIS separator operated around the clock for 6 days, processing 3 metric tons of uranium.

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Nonproliferation, arms control focus of Lab workshop

As a followup to a 1995 workshop in Snezhinsk, Russia, Russian and American scientists met at Livermore in September to explore the possibility of joint projects in arms control and nonproliferation technologies. Discussed at the workshop were possible collaborations on technical approaches to a wide range of international problems.

Principal attendees were from the Russian Ministry of Atomic Energy, the All Russian Institute of Experimental Physics, the All Russian Institute of Technical Physics, and Los Alamos, Sandia, and Lawrence Livermore National Laboratories. Also represented were the U.S. Departments of Energy, Defense, and State and the Russian Ministry of Foreign Affairs.

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Opportunities for Science from the Petawatt Laser

DURING the past 25 years, Lawrence Livermore has become a world-renowned research center for designing, building, and utilizing high-peak-power and high-energy lasers. Starting with the 100-million-watt, two-beam Janus laser in 1974, we designed and built a series of laser systems, each providing five to ten times more irradiance (power per unit area) than its predecessor.

Our series of increasingly more capable facilities now culminates in a revolutionary one-aperture laser, the Petawatt, with output power exceeding a quadrillion watts. Using the technique of chirped-pulse amplification, which enables us to produce very short (less than a trillionth of a second) energetic pulses on one arm of the ten-arm Nova laser, the Petawatt is able to exceed the total power of Nova by a factor of 10.

Even more impressive than its output power is the Petawatt's extraordinary brightness. Coupled with innovative focusing schemes, this brightness will enable the Petawatt to be focused to irradiances that produce an electric field exceeding by a factor of 100 the force that binds an electron to a proton in the hydrogen atom.

"Crossing the Petawatt Threshold," beginning on p. 4, describes the major technical and scientific advances that were required to make a petawatt laser a reality at Livermore. These advances in laser science and optical component fabrication have enabled revolutionary new concepts in laser science and machining as well as information display production technologies.

What's more, the enormous energy density of the Petawatt will push back the frontiers of knowledge about laser–matter interaction and expand our knowledge of matter under extreme conditions. For the first time in a laboratory setting, we will be exploring relativistic plasma physics and new sources of coherent and incoherent radiation at high photon energy.

Finally, the Petawatt will allow us to test a new pathway to laser fusion, called "fast ignition," that was developed at Lawrence Livermore early in this decade. As described in the article, the fast-ignition concept cleverly sidesteps the most difficult aspects of achieving fusion ignition with conventional inertial confinement fusion design.

The enormous opportunities created by the Petawatt will keep Lawrence Livermore in the forefront of high-power laser physics and high-energy-density physics for the foreseeable future.

■ E. Michael Campbell is Associate Director, Laser Programs.

Crossing the Petawatt Threshold

An extraordinarily powerful new laser promises to help make fusion power more easily attainable with "fast ignition." The laser beam's ultrashort pulses and extremely high intensities will also enable researchers to advance their understanding of the fundamental nature of energy and matter.

FOR more than three decades, Lawrence Livermore's Laser Programs have earned a worldwide reputation for pushing the limits of laser technology. But few accomplishments have rivaled the one celebrated in the early morning hours of May 23, 1996, by an exhausted but exuberant crew that just used a revolutionary laser that produced more than a quadrillion watts of energy, a world record.

The extraordinarily powerful laser is called the Petawatt because the prefix "peta" refers to a quadrillion, or 10^{15}. The laser reached a peak of 1.25 petawatts of peak power, about 25% more powerful than expected and more than ten times the peak power of Lawrence Livermore's Nova laser, the world's largest. The historic shots shattered the existing record for laser power (125 trillion watts) by more than a factor of 10, set by Livermore researchers using a Petawatt prototype during the summer of 1995.

Although the shots exceeded by more than 1,200 times the entire electrical generating capacity of the U.S., they lasted less than half a picosecond (a trillionth, or 10^{-12}, of a second). In that exceedingly fleeting moment, nearly 10,000 times shorter than the typical Nova laser shot, only enough energy (about 600 joules) was generated to keep a 100-watt light bulb burning for about 6 seconds.

By crossing the petawatt threshold, the laser heralds a new age in laser research. Lasers that provide a petawatt of power or more in a picosecond may make it possible to achieve fusion using significantly less energy than presently envisioned, through a novel Livermore concept called fast ignition. (See *Science & Technology Review*, September 1995, for more information.) The Petawatt laser will also enable researchers to study the fundamental properties of matter, thereby aiding the Department of Energy's stockpile stewardship efforts and opening entirely new physical regimes to study.

Coincidentally, University of California at Berkeley professor Charles Townes was visiting the Laboratory on the same day, May 23, as a member of a panel reviewing the Laser Programs (see Figure 1). Townes was awarded the Nobel Prize in 1964 for co-inventing the first laser, which generated only a few thousandths of a watt.

"When the laser first came along, I never imagined it getting up that high," Townes told reporters. "When we first invented them, I was thinking about very modest powers. It never occurred to me it would be in this kind of ballpark."

Indeed, the Petawatt is only the latest of a family of lasers with increasing irradiance (power per unit area) that began in the 1970s with LLNL's Argus, Shiva, and then Nova laser systems (see Figure 2). The introduction in the mid-1980s of a unique new laser material—titanium-doped sapphire (Ti:sapphire)—offered high gain over a broad range of wavelengths. Together with a new technology—chirped-pulse amplification (CPA) to minimize laser materials damage—they offered the possibility of creating high-power subpicosecond pulses directly from a solid-state laser. Lawrence Livermore researchers began work on short-pulse lasers in the mid-1980s and completed a 10-terawatt (TW) laser in 1989. The embodiment of most of the advances since that time resides in the Petawatt.

With its full-aperture beam of 58 centimeters in diameter (to be installed in early 1997 to replace a 46-cm beam), the Petawatt will produce about 1 kilojoule of energy in less than

Laser physicist Deanna Pennington adjusts a diagnostic lens within the Petawatt's compressor chamber. At right is one of the diffraction gratings, while behind her are a turning mirror and the second compressor grating.

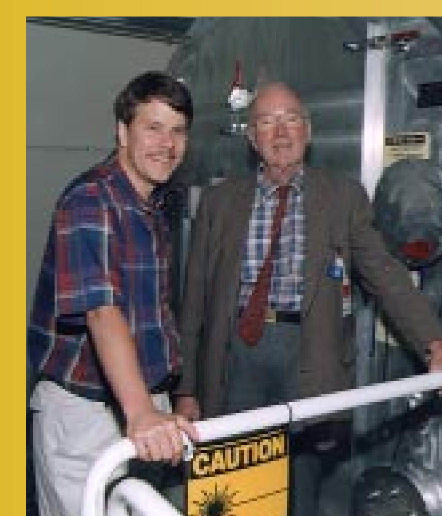

Figure 1. With the Petawatt is laser in the background, Livermore's Michael Perry (left) shows how far the technology has come to UC Berkeley Professor Charles Townes, who co-invented the laser.

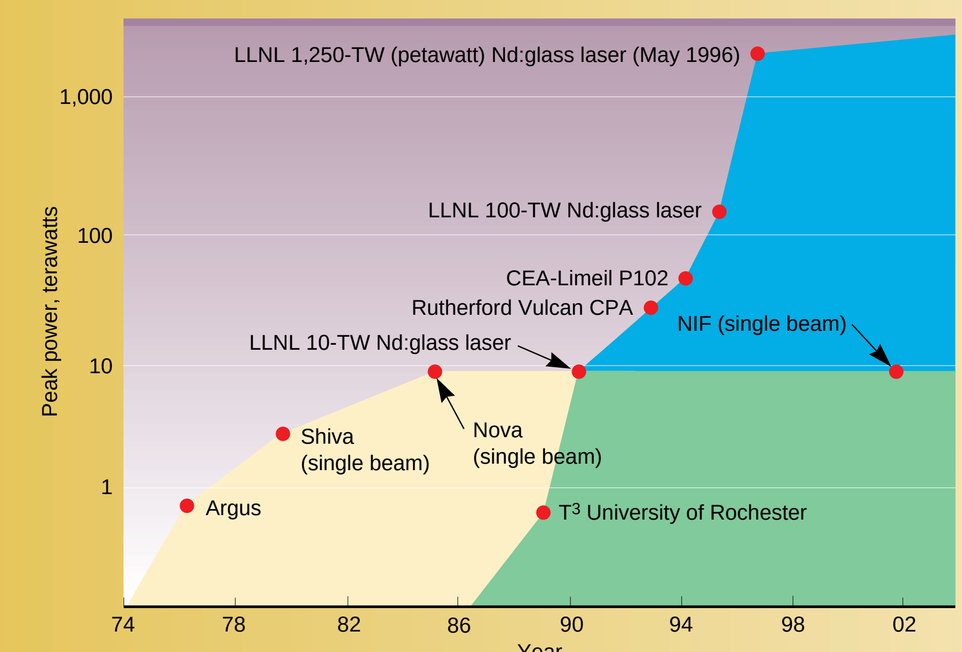

Figure 2. Milestones in laser development: early lasers (yellow), long-pulse technology (green), and chirped-pulse amplification technology (blue).

0.5 picosecond. In contrast, one beamline of Nova typically produces 10 kilojoules of energy in 1 nanosecond (billionth of a second), some 1,000 times slower. Nova and the National Ignition Facility (NIF) planned for Livermore are long-pulse lasers (nanoseconds and longer), specifically designed to produce high-pulse energy.

Petawatt Development

The Petawatt Advanced Fusion Project was proposed in 1992 as a high-risk, potentially high-payoff project to develop the capability to test the fast-ignitor concept for inertial confinement fusion (ICF) and to provide Livermore—and the world—with a unique capability in high-energy-density physics. Michael Perry, leader of Lawrence Livermore's Short-Pulse Lasers, Applications, and Technology Program, won a competitive grant in 1993 from LLNL's in-house Laboratory Directed Research and Development program to begin building the laser.

Perry formed a core team of physicists, engineers, and technicians with backgrounds in laser physics, optics, engineering, materials science, and atomic physics. Team members knew that success required advances in knowledge of the basic behavior of optical materials, development of new diffraction grating technology, substantial improvements in short-pulse laser technology, and advancement of a sound theoretical basis for the fast-ignitor concept. Finally, they recognized that although an all-Ti:sapphire laser could not provide sufficient power, a hybrid system starting with a Ti:sapphire laser and using new, smaller, and more efficient neodymium glass amplifiers could provide the necessary pulse energy and bandwidth to achieve a petawatt.

Much of the Petawatt's early effort was devoted to further developing CPA technology. CPA was first developed to increase the power of radar systems and was discussed for use in lasers in the middle 1970s. The first successful demonstration occurred for solid-state lasers in the late 1980s at the University of Rochester. Further developments at Rochester, Lawrence Livermore, and elsewhere along with the introduction of new laser materials (e.g., Ti:sapphire) have revolutionized high-power laser research. (See Figure 3.)

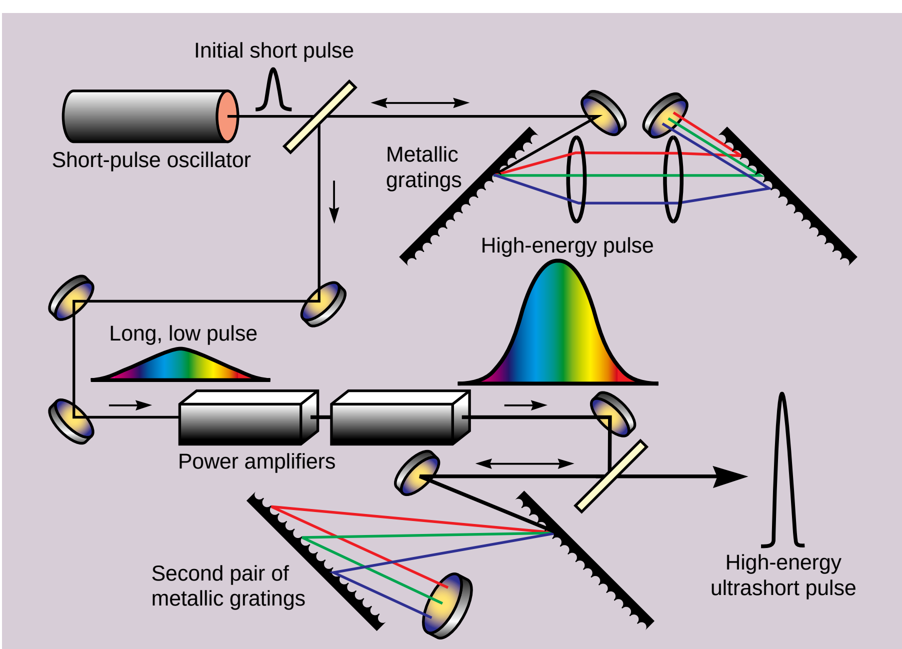

Figure 3. The concept of how chirped-pulse amplification and other new technologies enable the production of the petawatt (quadrillion-watt) pulses.

CPA is critical because laser pulses of extremely high power density (gigawatts/centimeter^2, or GW/cm^2) can severely damage optical components such as amplifiers, lenses, and mirrors. With CPA technology, it became possible to generate very short laser pulses with extremely high peak powers by stretching a low-energy laser pulse more than 10,000 times its duration prior to amplification and then recompressing the pulse back to near the original duration after amplification. Because passage through the laser optics occurs when the pulse is long, there is no damage.

Using this technology, the Petawatt laser begins with a broad-bandwidth, low-power pulse lasting less than 0.1 picosecond in a temperature-controlled clean room in the basement of the Nova building. Instead of consisting of a single, very specific wavelength (color) produced in conventional lasers, these ultrashort pulses contain a broad spectrum. Before amplification, the short-pulse beam is sent to the pulse stretcher. Here, the pulse is stretched by using a diffraction grating to spread out the different wavelengths (colors), separating each frequency component. By passing each color through a different optical path length (the red components travel a shorter length than the blue), the pulse is stretched in time by a factor of 30,000 to 3 nanoseconds. The pulse is then amplified more than a trillion times without damaging the laser glass as the pulse travels through a series of amplifier modules, including a portion of one arm of the Nova laser for the final amplifier stage.

After amplification, the beam is then sent to the vacuum chamber 3 × 11 meters long, where the pulse is

compressed using a pair of diffraction gratings each 74 centimeters in diameter. By reversing the process of the stretcher (now the red components travel a longer length than the blue), the pulse is compressed down to less than half a picosecond (nearly its original duration), thereby increasing its peak power nearly 10,000 times to more than a petawatt. Such pulses must be compressed in a vacuum because the irradiance of the beam leaving the second grating is over 700 GW/cm^2, far too great to pass through any material (including air) without resulting in damage.

The Grating Challenge

One of the most challenging tasks was the fabrication of pulse compression gratings of sufficient size, optical quality, and ability to withstand the enormous power of the Petawatt laser pulse. Said Perry, "When the project began, there wasn't a facility in the world capable of making the required gratings, so we created one."

The diffraction gratings that are used in the Petawatt laser are nearly 1 meter in diameter, some eight times larger and twice as resistant to damage as the previous state of the art. Livermore's successful development of diffraction grating technology for the Petawatt led to the selection of gratings for many uses on the National Ignition Facility (NIF), a 192-beam laser facility planned for Livermore.

Initially, achieving a petawatt of peak power was expected to require an entirely new optical component—a high-efficiency, multilayer dielectric grating. That advanced technology was developed by the Petawatt team in 1993 and 1994, an achievement recognized in 1994 with an R&D 100 Award. However, the dielectric gratings were not used in the current experiments because new metallic gratings developed by the team have proven satisfactory for petawatt pulses at 0.5-picosecond durations. These metallic gratings are simpler to manufacture than the multilayer gratings. Multilayer gratings would be required to achieve the multikilojoule pulses necessary to achieve ignition if fast-ignitor capability is added to the NIF. Interestingly, the multilayer dielectric grating technology has already produced its own spinoff. (See this and other spinoff technologies discussed in the box below.)

With the grating technology in hand, the focus of the Petawatt team moved to installation of the petawatt system on the Nova laser. Numerous large-scale optical and mechanical components capable of working at extreme precision under vacuum had to be designed,

Petawatt Spinoffs

The technology developed for the Petawatt has provided many unexpected spinoffs. In particular, Lawrence Livermore's experimental and theoretical studies of laser-induced damage, carried out in support of the Petawatt laser's development, have created valuable new technologies. Researchers, led by Brent Stuart, using the petawatt front end made pioneering measurements of the laser damage threshold for a multitude of optical materials (crystal and glass) lasting from 0.1 picosecond to 1 nanosecond. A fundamental change in the damage mechanism is observed when the pulse length is less than approximately 20 picoseconds. This change in mechanism is accompanied by a dramatic change in the morphology of the damage site.

The discovery and explanation of this difference formed the basis of a collaborative program with medical researchers on the interaction of short laser pulses with human tissue. Laser ablation of tissue (removal of tissue by its being "blown off") has great promise in a number of therapeutic situations requiring precise material removal with minimal disturbance of the surrounding tissue. Potential applications include precision cutting (as in keratonomy), perforation (applicable to middle ear surgery), pressure release for hydroencephaly, and dental drilling. The advantage for surgery with lasers whose pulses last less than a picosecond is that the duration is far too short to transfer heat to surrounding tissue. (See the October 1995 *S&TR* for more on LLNL efforts to develop short-pulse lasers as safe and painless surgical tools.) The ability to cut and drill material with no heat or shock has also found important application in LLNL's role in nuclear weapon stockpile management.

Two R&D 100 Awards were earned as a result of the need to manufacture diffraction gratings to a size, precision, and resistance to optical damage never before attained. The first, earned in 1994, was the development of multilayer dielectric gratings for use in dispersing light into constituent colors, or wavelengths, for many different applications. These gratings, made of multiple layers of thin dielectric film, have much higher damage thresholds than metallic gratings and can be custom designed for narrow- or broad-bandwidth use. Besides their use in new generations of extremely high-powered lasers, they may be used in entirely new products in such areas as remote sensing and biomedical diagnostic systems. (See the September 1994 *E&TR* for more information.) Furthermore, the grating development laboratory and technology will be used for developing the extensive diffractive optics used throughout the final focus assembly of the planned National Ignition Facility.

The technology developed to produce the multilayer and metallic gratings with extremely small features (down to 0.1 micrometer) may also give a dramatic boost to American producers of flat-panel displays. The LLNL process to laser interference lithography enables the production of large-area field-emission displays (FEDs). This display can be thinner, brighter, larger, and lighter and can consume less power than traditional active matrix liquid crystal displays. The new technology earned its inventors an R&D 100 Award in 1996 (see the October 1996 *S&TR*).

fabricated, and installed. Significant modifications to the ten-beam target bay were performed over many weekends, when the Nova laser is usually not used for target experiments. A new beamline was installed to route the beam from the Petawatt's master oscillator room to the disk amplifier section of Nova's beamline number 6 for final amplification. A particularly challenging task was installation of the enormous compression chamber in the target bay without disrupting the normal operation of the Nova system.

With everything in place, three series of experimental shots were performed. In the first series, performed in December 1994, the Petawatt's beam was propagated to Nova's two-beam target bay to study CPA effects. For the second shot series, performed in March 1995, the beam was propagated into the newly constructed compression chamber to produce a short pulse length. Following the March 1995 shot series, the new injection beamline between the Petawatt's master oscillator room and the Nova preamplifier was activated, along with the compression chamber vacuum system and a full suite of optical diagnostics. The final test series performed in May 1996 produced the record-shattering result, but not without exceptionally hard work. "We had to work 16-hour days, 7 days a week for more than a month to make sure everything was ready for the demonstration shots. It was a true team effort between the Nova engineers, operations crew, and the Petawatt project team," recalls Perry, who furnished non-alcoholic champagne for the historic night. (See Figure 4.)

Four Options

As the Petawatt laser is now configured, the beamline from the underground master oscillator room can take one of four courses. First, it can be injected into the Nova chain to the Petawatt's compressor chamber and used along with nine of Nova's ten beams as a large-scale hybrid system to test the fast-ignitor concept and investigate new concepts in laser–matter interactions and plasma physics. Second, the beam can be shunted to a small room next door to the master oscillator room, where it is used for researching issues related to the use of lasers in medicine and material processing, development of plasma mirrors, and harmonic conversion to a shorter wavelength for Nova x-ray diagnostics development.

Third, through early next summer, the laser can be used as the core of a 100-trillion-watt laser to study plasma physics and begin research on fast-ignitor physics. Finally, early this winter, a target chamber will be

Figure 4. The Livermore crew after the first successful accomplishment of petawatt peak power (1,250 trillion watts) on May 23, 1996.

installed between the Petawatt's compression chamber and Nova's ten-beam chamber. It will permit the Petawatt laser to be used independently of Nova.

The decision to develop a target chamber exclusively devoted to petawatt laser use, while retaining the ability to perform experiments in Nova's ten-beam target chamber, was prompted by the high level of interest expressed by researchers at LLNL and other centers.

Building a petawatt target chamber makes good sense, says Perry, "because it will allow us to work the bugs out of the Petawatt's focusing system and enable simple, single-beam experiments without impacting operation of the Nova chamber."

The 100-TW laser was constructed in early 1995 as a crucial stepping stone to the Petawatt. Using most of the Petawatt's components, but not taking advantage of the full complement of Nova's amplifiers, the 100-TW is connected to Nova's two-beam target area. It was successfully test fired for the first time on July 31, 1995, surpassing the 120 trillion watts produced by Nova and making it the most powerful laser ever tested at the time.

"The 100-TW was only a warm-up for the Petawatt," says project engineer Greg Tietbohl, noting that the laser has been used to test some of the basic concepts and advanced components underlying the Petawatt. Laser–plasma experiments being performed on the 100-TW laser are producing data that enable the design of a more comprehensive series of experiments to test the fast-ignitor concept on the Petawatt. The 100-TW laser continues to operate as the world's second most powerful laser, and it is now used extensively by researchers from LLNL and the international university community. The 100-TW operations will end in July 1997 because Nova's two-beam target bay will be disassembled in order to build an optics assembly area for NIF.

Focusing Petawatt Pulses

A significant problem with petawatt pulses is how to focus them. Conventional approaches such as lenses or mirrors with debris shields cannot be used because these both involve transmissive optics that would be damaged by the extreme power density of the petawatt pulse (over 700 GW/cm^2).

A radical concept proposed by Perry and Associate-Director-at-Large John Nuckolls was the use of a so-called "plasma mirror." The intense petawatt beam strikes the front surface of a piece of polished glass, creating a very-short-lived critical-density plasma in the early part of the pulse. Because the petawatt pulse is so short, the plasma does not have time to expand during the pulse. The remainder of the pulse then reflects off the critical-density plasma and strikes the target of interest.

The resulting detonation of the target creates a large amount of debris (typical of all target experiments) that hits the plasma mirror substrate instead of sensitive and expensive diagnostic equipment and optics. (See Figure 5 for the difference in optical- and plasma-mirror irradiances.) The curvature of the mirror can be easily changed to accommodate a wide variety of experimental conditions and targets. To date, over 90% reflectivity has been demonstrated in small-scale experiments conducted with the Petawatt's front end.

Possible Key to Fast Ignition

The Petawatt provides researchers with their first tools to explore the fast-ignitor fusion concept, conceived by Livermore's Max Tabak and others in 1992. Focusing a high-power laser pulse gives rise to an extremely high density of energy, or light pressure. This light pressure can enable the laser pulse to interact with very-high-density material at the core of an imploded fusion pellet instead of being stopped by lower-density plasma in the corona. These intense pulses also generate large amounts of energetic electrons. These high-intensity phenomena form the basis of the patented fast-ignitor fusion concept. (See Figure 6.)

In this scheme, laser energy compresses a spherical volume of fusion fuel to high density—exactly as in the conventional approach to ICF. However, conventional ICF relies on the formation of a hot central core

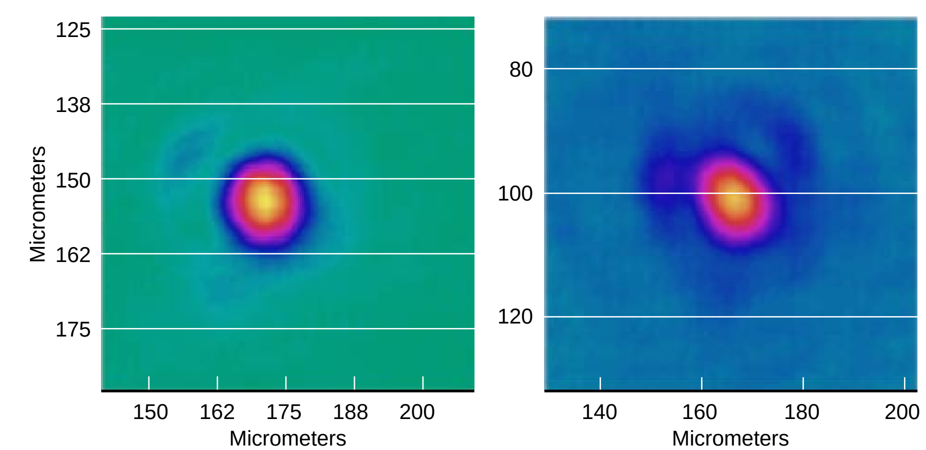

Figure 5. False-color contour plot of far-field irradiance distributions from (a) a precision optical mirror (diffraction-limited spot) and (b) a plasma mirror.

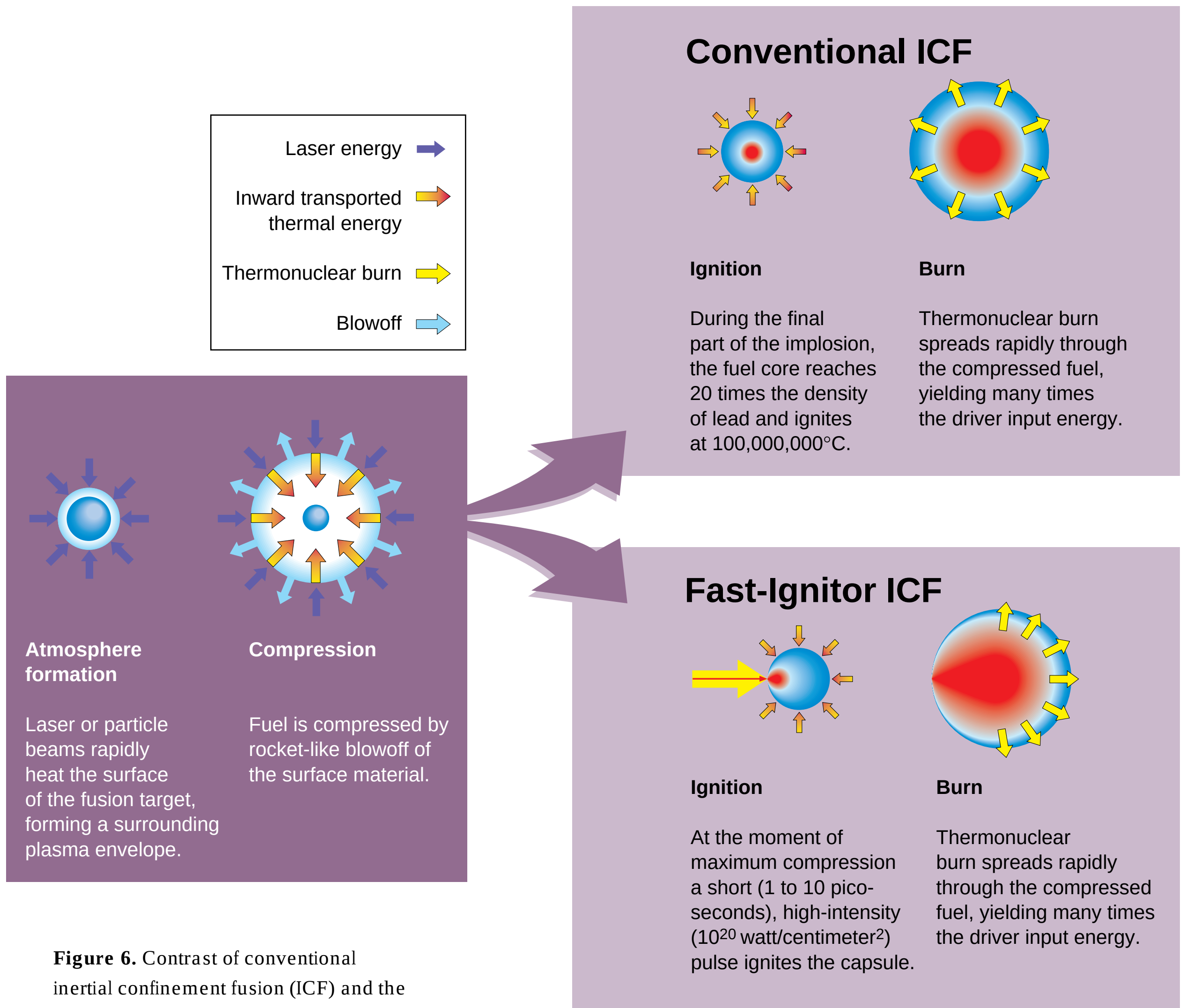

Figure 6. Contrast of conventional inertial confinement fusion (ICF) and the fast-ignitor ICF, which is used on the Petawatt laser.

within the dense deuterium–tritium fuel to spark ignition. This condition is achieved by the rapid, highly symmetrical and spherical implosion of the capsule driven by pulses delivered either directly by many laser beams or indirectly by x rays. Because of the extreme requirements on symmetry and the necessity to achieve both high temperature and density in the implosion, conventional ICF requires substantial energy and precision from the laser.

By contrast, the fast-ignitor concept adds two laser beams that are timed to strike the target at the moment of maximum compression. Because the Petawatt was conceived to use Nova, eight of Nova's ten beamlines would strike the target and form a plasma. Then a 1-TW, 100-picosecond channeling beam supplied by the Petawatt laser bores through the plasma and pushes the deuterium–tritium fuel in its path toward a higher density near the core of the target. At the optimum moment, a petawatt ignitor beam propagates through the channel formed by the channeling beam, striking the high-density, preimploded core. The petawatt pulse generates hot, high-energy electrons, which instantaneously raise a small region on the periphery of the core to over 100 million degrees Celsius. The fusion burn propagates from this small volume on the edge throughout the remaining fuel before hydrodynamic disassembly of the core.

The fast-ignitor technique offers, in principle, a method of reducing the energy and precision required to achieve ignition compared with conventional ICF. Perry cautions that, compared with the firm scientific foundation of conventional ICF, the fast-ignitor concept is still in its infancy because it resides in a region of untested physics. If, however, upcoming fast-ignition tests prove successful, a petawatt laser could be added to the NIF for fast-ignitor capability at a moderate additional cost.

The Petawatt's beam would be fired to inject energy into a small region of the deuterium–tritium target capsule to initiate ignition a few billionths of a second after NIF's beams are fired. A Petawatt–NIF combination might enable the achievement of a higher fusion energy gain than currently envisioned.

A New Chapter in Physics

The ultrashort pulses and extremely high irradiance of the Petawatt laser will also enable researchers to advance their understanding of laser–matter interactions and, indeed, advance understanding of the fundamental nature of energy and matter. The enormous irradiance that will be generated by the Petawatt, some 10^{21} W/cm^2, will make possible an irradiance unlike any produced in the laboratory to date. These unprecedented laboratory conditions will be characterized by electric fields about 100 times stronger than the field that binds electrons to atomic nuclei. Such fields have the potential to trap electrons and accelerate them to high energies within just a few centimeters, instead of many kilometers as in conventional particle accelerators.

The enormous electric fields created by the Petawatt will impart enormous oscillatory ("quiver") energy to the free electrons in the plasma. At 10^{21} W/cm^2, the quiver energy of a free electron would be more than 10 million electron volts. The electrons would be moving at speeds approaching the speed of light and at densities never before seen in the laboratory.

These plasmas will be similar to those believed to exist in many astrophysical objects. Scientists could then study conditions predicted to exist in the center of stars and surrounding celestial bodies such as black holes and brown dwarves.

Additionally, high-energy photons (0.1 to 10 megaelectron volts) produced from the interaction of the petawatt pulse with high-atomic-number targets offer the potential for time-resolved radiography of dense objects. The short-pulse duration, potentially small source size, and simple production of multiple pulses separated in time make this an attractive source for multiple-exposure flash x-ray radiography. The plasmas themselves can provide important information to Lawrence Livermore scientists supporting DOE's Stockpile Stewardship and Management Program.

The Petawatt laser is currently undergoing a long series of tests as it is transformed into an operational facility for target experiments. Its development is expected to continue into the next decade as LLNL scientists continue to advance the state of the art in optics and the technology of short-pulse lasers. Perry notes that several years of hard work lie ahead in exploring the fast-ignitor concept with the Petawatt. The overall goal, as it was with the development of Livermore's first generation of lasers, is to speed the arrival of laser fusion as a source of virtually inexhaustible energy for society. Another goal, admittedly closer at hand, is to aid the nation's Stockpile Stewardship Program.

Key Words: chirped-pulse amplification, fast ignition, laser interference lithography, multilayer dielectric gratings, National Ignition Facility, Nova, Petawatt laser, plasma mirror, Ti:sapphire laser, 100-TW laser.

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About the Scientist

MICHAEL PERRY joined Lawrence Livermore National Laboratory as a physicist in October 1987. He is a graduate of the University of California at Berkeley with a B.S. in both nuclear engineering and chemical engineering (Summa Cum Laude, 1983), an M.S. in nuclear engineering (1984), and a Ph.D. in nuclear engineering/physics (1987). He is currently the leader of the Petawatt Laser Project and Associate Program Leader for Short-Pulse Lasers, Applications, and Technology. He has authored more than 70 professional publications.

High Explosives in Stockpile Surveillance Indicate Constancy

Livermore actively seeks to improve the analysis of high explosives in stockpiled nuclear weapons, keeping in mind the purposes of traditional surveillance: to look for defects in materials and processes, to monitor indicators of both constancy and change, and to confirm that design choices did not cause problems.

ANY weapon in the U.S. nuclear arsenal, if ever deployed, must work exactly as intended. Americans expect that assurance even though international relations since 1989 have brought dramatic and fundamental changes to the U.S. nuclear weapons program. Responsibility for assuring reliability, performance, and safety of the nuclear weapons stockpile belongs to the nuclear design and production community, which conducts the wide range of activities in the Department of Energy's New Material and Stockpile Evaluation Program.

Although stockpile evaluation is not new, methods and tests have undergone marked changes since the program's inception almost four decades ago. Today, each of the participating national laboratories—Lawrence Livermore, Los Alamos, and Sandia—is responsible for the extensive and rigorous tests to evaluate the portions and components of the stockpile weapons that each has designed. This overview of Livermore high-explosives (HE) tests of nuclear stockpile weapons illustrates the degree of assurance toward which the laboratories work.

Stockpile Evaluation

"Stockpile surveillance" is the third, or maintenance, phase of a spectrum of special tests that begins during a weapon's design and ends only with its retirement from the stockpile (see box on p. 13 and Figure 1). Such tests now are the principal means of evaluating the condition of U.S. nuclear weapons. For this phase, stockpile laboratory tests provide "indicators of constancy" through comparison with baseline data gathered during weapon development and production.

Stockpile laboratory tests usually begin during the third or fourth year after the weapon's production begins. Sample weapons removed from the stockpile are dismantled, components are inspected and tested, and then the weapons are reassembled and restored in the stockpile. Increasingly, surveillance activities have focused on one central question: How can a weapon's useful service life be predicted?

In addition to checking for materials and production defects, stockpile surveillance involves monitoring potentially damaging changes to a weapon's components caused by aging or environmental factors. Simply because nothing is wrong, the inference cannot be made that the weapon will last indefinitely. Livermore's Enhanced Surveillance Program is currently examining concepts that improve predictive capabilities.

Should problems appear, the increasing body of data will guide the program to accommodate or eliminate adverse effects. Old or damaged parts are replaced or upgraded before a weapon is reassembled for the stockpile. This aspect of surveillance resembles keeping a stored car in driving condition. Regular inspections can spot signs of damage or deterioration before they become too costly to repair. The vehicle can also be upgraded by installing improved replacement parts.

High Explosives

The ideal high-energy explosive must balance different requirements. HE should be easy to form into parts but resistant to subsequent deformation through temperature, pressure, or mechanical stress. It should be easy to

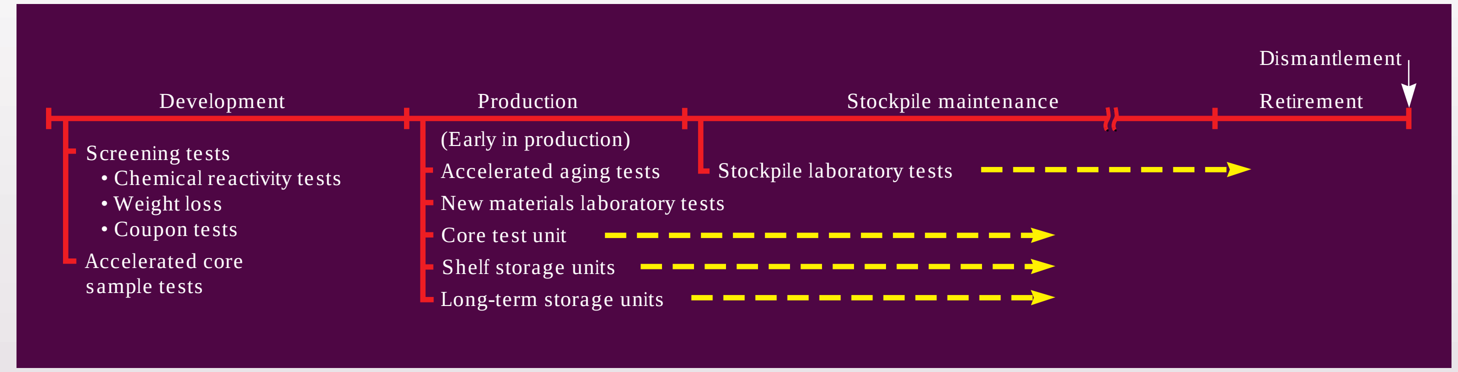

Figure 1. Phases of evaluation in stockpile surveillance.

detonate on demand but difficult to explode accidentally. The explosive should also be compatible with all the materials it contacts, and it should retain all its desirable qualities indefinitely.

No such explosive existed in 1944. While using what was available to meet wartime demands, scientists at Los Alamos began to develop a high-energy, relatively safe, dimensionally stable, and compositionally uniform explosive. By 1947, scientists at Los Alamos had created the first plastic-bonded explosive (PBX), an RDX[*]-polystyrene formulation later designated PBX 9205. Although other PBXs have since been successfully formulated for a wide range of applications, only a handful have displayed the combination of adequate energy content, mechanical properties, sensitivity, and chemical stability required for stockpile nuclear weapons. Since the 1960s, Livermore has been researching and developing safer HE for Livermore-designed weapons.

The plastic coating that binds the explosive granules, typically 5 to 20% of each formulation by weight, is what gives each PBX its distinctive characteristics. Pressing a PBX molding powder converts it into a solid mass, with the polymer binder providing both mechanical rigidity and reduced sensitivity to accidental detonation. The choice of binder affects hardness, safety, and stability.

Too brittle a PBX can sustain damage in normal handling and succumb to extreme temperature swings or thermal shocks, while too soft a PBX may be susceptible to creep and may lack dimensional stability or strength. To achieve safe and stable PBXs, the Laboratory uses two main charge explosives based on HMX and TATB.[†]

HMX is more energetic than RDX but retains good chemical and thermal stability, important for long-term storage and survival in extreme environments. Sensitivity of any PBX is a complex characteristic strongly affected by HE particle size distribution, viscoelastic properties, binder-to-HE wetting, and storage environment. Only the TATB-based formulations (Figure 2) of Livermore's

HE's Role in a Nuclear Weapon

The nuclear explosive package includes nuclear and non-nuclear components that comprise a primary explosive device and a secondary, both enclosed within a radiation-proof case. A key component of a primary is typically a shell of fissile material—the pit—to be imploded by a surrounding layer of chemical high explosive (HE) termed the main charge.

Stockpile evaluation requires a comprehensive battery of tests that addresses all functional aspects of a weapon throughout its so-called stockpile-to-target sequence, stopping short of actual detonation with nuclear yield. Although the moratorium on underground nuclear testing has precluded detonating a stockpile weapon to assess its reliability, performance, and safety, stockpile evaluation is working to provide an adequate alternative route to the same goal of reliability assessment.

The HE clearly plays a role vital to proper weapon function, but many questions surround the long-term stability of the complex organic molecules of which the HE is composed. To provide assurance that stockpile quality is maintained, Livermore's Stockpile Evaluation team develops diagnostic tests that are performed on the HE in the main charges of stockpile weapons.

* RDX is 1,3,5-trinitro-1,3,5-triazacyclohexane.

† HMX is 1,3,5,7-tetranitro-1,3,5,7-tetrazacyclooctane; TATB is 1,3,5-triamino-2,4,6-trinitrobenzene. See *S&TR*, November 1996, for more information on TATB.

LX-17 and Los Alamos's PBX 9502 are considered "insensitive" high explosives (IHE); others are termed "conventional."

Evaluating the Package

Livermore is responsible for surveillance of the stockpile weapons that are based on its own designs. The Engineering Directorate and the Defense and Nuclear Technologies Directorate collaborate on Livermore's Stockpile Surveillance Program. General procedures for the annual evaluation begin with a predetermined number of samples of each weapon type chosen at random from the stockpile. All are disassembled to varying degrees for evaluation, but typically only one weapon has its explosive package reduced to its component parts: pit, explosive, detonators, and secondary.

Livermore mechanical engineers and materials scientists develop prototype tests, and then Pantex workers perform the tests on actual stockpile weapons components and materials. The tests focus on what would alter the estimated minimum warhead life or require retrofitting.

The complete evaluation entails four major investigations, each with rigorous safety and technical protocols: (1) examining the HE for changes in appearance and texture, including surface discoloration, cracks (using dye penetrant), or tackiness of any materials; (2) measuring physical and mechanical (tensile, compressive) properties, including density and contour; (3) measuring chemical properties, including HE and binder composition, binder molecular weight, and warhead atmosphere analysis; and (4) conducting performance tests, including pin hydrodynamic tests, "snowball" tests, and detonator test firing or disassembly.

In characterizing materials, Livermore surveillance addresses interrelationships among components. Environmental factors such as radiation, heat, and chemical incompatibility can affect the behavior of components and their interfaces throughout the initiation chain: the detonator, booster, and main charge. Explosives could also suffer aging effects in such properties as creep, growth and density gradients, thermomechanical integrity, initiation capability, detonation performance, sensitivity, and safety.

These concerns are addressed during the warhead's development and early production phases, largely through tests using accelerated aging techniques (primarily elevated temperature) to simulate the long-term effects of internal and external environment. The main goal of accelerated aging tests is determining whether materials, parts, and assemblies are compatible with each other and retain their essential properties.

During surveillance, actual aging and environmental effects are evaluated, using new materials laboratory tests and material qualification test results as baseline data.

Tests of Physical Properties

Density and density uniformity are parameters easily measured with high precision. If HE chemical and density distributions remain substantially constant during storage, no significant change is expected in specific energy or detonation velocity.

Figure 2. TATB material is being prepared for an aging test.

Figure 3. High-explosives chemist Mark Hoffman sets up HE for mechanical tests.

In both stockpile laboratory tests and accelerated aging tests, density distribution is measured using cored samples. These measurements are then compared with recorded densities from each material lot. Laboratory test results show that accelerated aging conditions do not significantly alter the uniformity of HE density; density actually becomes more uniform throughout the main charge.

Tests of Mechanical Properties

As an integral part of the explosive package's structure, HE must retain its own structural integrity. Therefore, tensile and compressive mechanical properties of HE are monitored (see Figure 3). These mechanical properties were found to be correlated with HE composition and density, as well as the crystallinity and nature of the polymeric binder. Mechanical properties may also be affected by changes in the properties of the explosive–binder interface, but these can only be addressed indirectly.

Tensile strength testing. Tensile tests are performed on LX-17, for example, at a low temperature (–20°C) and a slow rate because these conditions simulate the expected worst case (due to thermal expansion mismatches of the materials). This test best shows differences in material quality. Test data for three Livermore weapon systems show no apparent aging trends in LX-17 tensile stress and strain at failure.

Compression testing. For simulating the worst-case conditions for creep (displacement under fixed load) in the warhead, compression tests are performed on LX-17 at an elevated temperature (50°C) and a slow rate (1,440 microstrain per hour).

In surveillance testing, compression values for LX-17 have not failed or fallen outside of material qualification limits. Data on stockpile-aged material from the W87 warhead, however, do show an apparent stiffening of the LX-17 with age (see Figure 4). Although this phenomenon may actually reflect an increase in the crystallinity of the binder, the LX-17 continues to be monitored and will be compared with the behavior in other systems.

Tests of Chemical Characteristics

As HE ages or degrades, its compatibility with other materials in the primary may suffer. Thus, several types of analysis are employed to evaluate the HE's chemical composition.

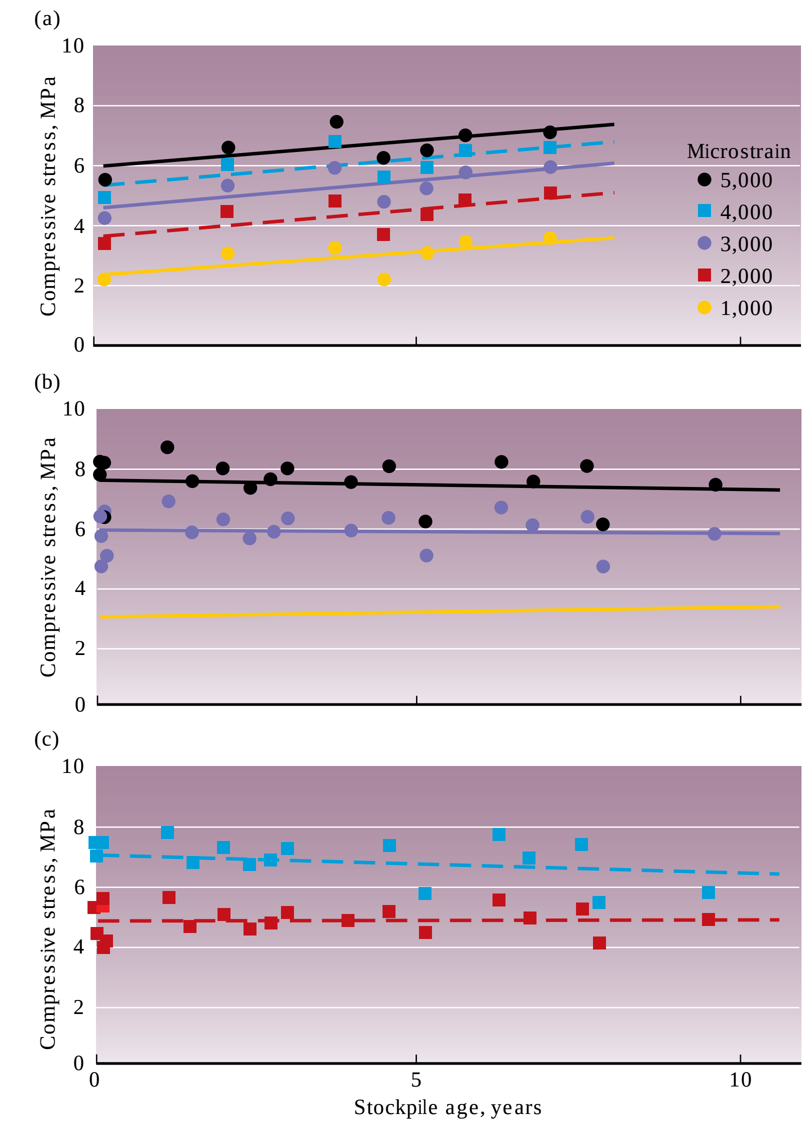

Figure 4. (a) The compressive stress tests for the LX-17 high explosive recovered from the W87 new materials laboratory test (NMLT) units and stockpile laboratory test (SLT) units. The data show a stiffening of the LX-17 at all strain levels, which may be consistent with a gradual increase in the crystallinity of the Kel-F-800 binder. For reasons not clear at this time, this trend is not supported by the observations from the B83 (b) NMLT units and (c) SLT units.

Chemical composition analysis. Relative percentages of binder and HE are compared with values obtained from qualification tests of newly produced HE. Percentages of HE different from nominal values could signal significant chemical degradation, which would mean lower energy density for LX-17. To date, however, aging has not affected chemical composition. Changes, if any, remain too subtle for current analytic techniques.

Molecular weight analysis. For this analysis, the polymer binder is extracted from the HE and subjected to gel permeation chromatography (also called size exclusion chromatography). Current techniques have yet to reveal significant aging effects on the molecular weight or molecular weight distribution of LX-17 binder. Small changes in molecular weight that might indicate the onset of degradation, however, are very difficult to detect and characterize. In Livermore's Enhanced Surveillance Program, methods are being developed to improve the ability to detect aging effects.

Warhead atmosphere gas sampling. Mass spectroscopy and gas chromatography of warhead gas samples can identify material outgassing and ongoing chemical reactions, both of which may indicate degradation or decomposition of the organic compounds in the HE. They also help to verify whether warhead environmental seals have leaked.

(a)

(b)

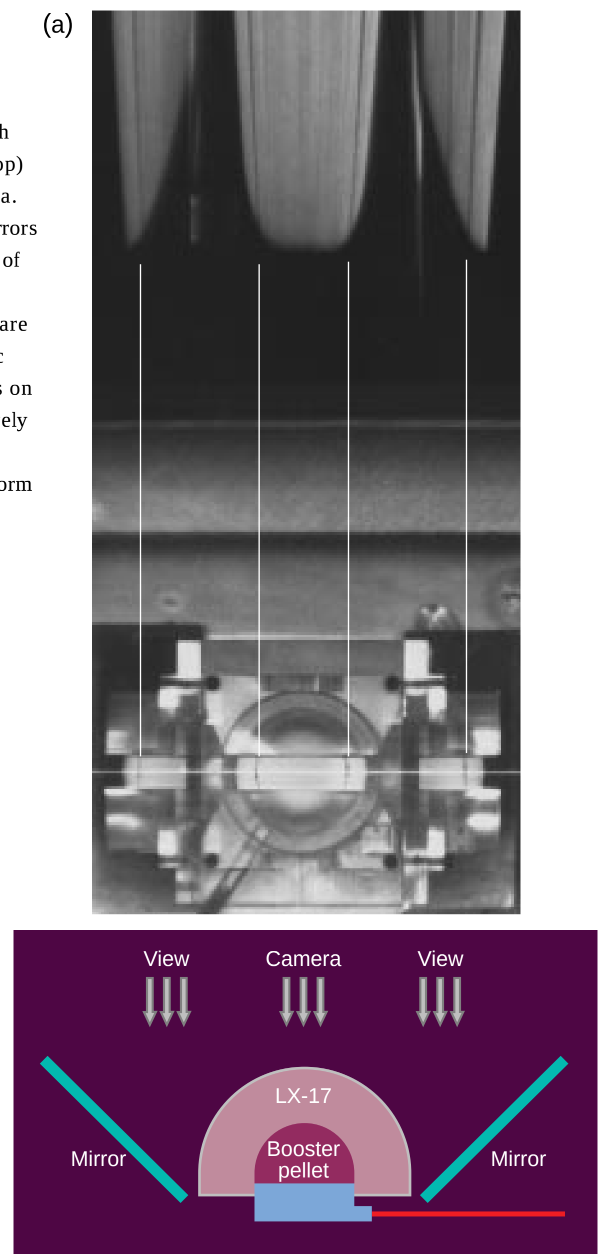

Figure 5. (a) A "snowball" test assembly (bottom) is aligned with samples of snowball test data (top) as recorded by the streak camera. (b) The schematic shows the mirrors that reflect the left and right sets of snowball data.

For illustration, vertical lines are drawn between the photographic breakout record and the markers on the snowball surface. The relatively flat curves at the bottoms of the image data indicate a good, uniform explosion.

Performance Tests

Performance tests tell about the detonation response of the material. Pin hydrodynamic tests check the implosion reliability and performance of the main charge; "snowball" tests help determine the initiation reliability of the booster. Detonators also are test-fired, and certain ones are disassembled for inspection and analysis.

Pin hydrodynamic test. This test monitors changes in the implosion behavior of HE. The test assembly comprises three main subassemblies: a pin-dome assembly, a mock pit, and the HE. The test measures elapsed time from initiation until the explosive drives the mock pit into an array of timing pins, a "pin dome," of known length and location. The HE implodes the mock pit onto the timing pins, which provide data about the temporal and spatial uniformity of implosion. A nonuniform implosion could indicate an HE problem. Excessive density variations, voids, or cracks in the HE, for example, can disrupt the shock-wave propagation from the detonation. To date, surveillance testing has observed none of these problems in stockpile samples.

Snowball test. This test checks reliability of the initiation chain by confirming that the booster initiates the HE. A machined shell of LX-17 is assembled with a booster and detonator to form a "snowball." When this assembly is fired, a streak camera captures spatial and temporal information of the initial, or "breakout," detonation wave on the outer surface of the LX-17 snowball (see Figure 5). The relatively flat curves at the bottom of the image data indicate a good, uniform explosion. Changes in the breakout profile would be used to track the performance of the booster and the condition of the interface with the HE.

Aging tests. So far, surveillance data on HE from the B83, W84, and W87 programs show no evidence of aging effects. Because the W87 system must be requalified for an additional 25 to 30 years, additional data are being gathered and analyzed to improve Livermore's long-term predictive capability. Aged LX-17 is being subjected to far more comprehensive testing than usual for stockpile laboratory test units. In essence, properties of control material from various sources are compared to the chemical, physical, mechanical, and performance properties of aged LX-17 for signs of age-induced changes.

Changes, if any, will be studied further in the Enhanced Surveillance Program. Should no changes be discovered, confidence in the projected longevity of the W87's HE materials will be scientifically supported.

A compatibility program initiated during W84 warhead production is paying dividends by serving as a source of aged materials for advanced study. Some specimens of LX-17, UF-TATB (ultrafine TATB) boosters, and LX-16 pellets from W84 production are already being subjected to accelerated aging in a weapon-like atmosphere for ten years.

The Next Step in Surveillance

Continually sought to improve the analysis of HE in weapons in the stockpile, technologies must still fulfill the purposes of traditional surveillance. First, early in a weapon's stockpile life, materials and processes are scrutinized for defects, and then they are monitored to confirm that design choices do not cause problems.

Other improvements are being evaluated for inclusion in the program: (1) fundamental understanding of aging mechanisms in stockpile materials, (2) better selection of stockpile samples for testing and evaluation, (3) better uses of available materials (stockpile-aged materials, such as those from retired and dismantled weapons), and (4) peer review of surveillance data.

Accordingly, the Livermore Stockpile Surveillance Program has proposed revisions in the surveillance mission to achieve the following capabilities:

- Detecting and identifying changes in stockpile-aged materials that previous surveillance methods may not have discovered.
- Predicting—not simply monitoring—any identified age-induced changes in materials through the use of models.
- Providing information on aged materials to weapons designers, who can assess effects on weapons performance.
- Verifying the safety of aged materials via testing and modeling.

These changes will help improve an already successful Livermore stockpile evaluation program. They will enhance surveillance techniques to assure the nation and its armed forces that Livermore-designed weapons can be safely stored and transported and that they can work exactly as intended throughout their stockpile life.

Key Words: accelerated aging, high explosive (HE), LX-17, nuclear weapon, PBX, pin-dome test, predictive capability, snowball tests, stockpile evaluation, stockpile surveillance, TATB.

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About the Engineer

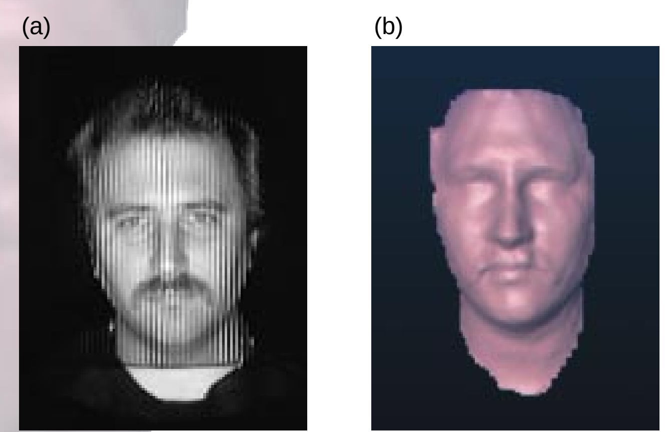
ANDERS W. LUNDBERG has supported nuclear weapons engineering and testing at Lawrence Livermore since 1961. He received both his B.S. and M.E. in mechanical engineering from the University of California at Berkeley in 1959 and 1961, respectively. At Livermore, he has been a project engineer and group leader in the Weapons Program and the Nuclear Test Program; currently, he is group leader for Stockpile Surveillance in the Mechanical Engineering Department.

Visualizing Body Motion

WHEN you think about it, lots of people could use the knowledge obtained from capturing, re-creating, and analyzing body motion in 3-D (three-dimensional) form. One group might be specialists: orthopedic surgeons, to plan surgery or physical therapy; athletes, to maximize their training and performance; robotic engineers, to "teach" robots how to interpret motion; and animators and video game designers, to make their animations more realistic. Another group might be the folks who want to understand their own common ailments, such as repetitive motion problems or tendonitis.

Studying body motion is not a new activity, but the data-gathering techniques for these studies have changed over the years. Currently, one common way of collecting motion data is by attaching reflective markers on a human actor at strategic points—on shoulders, elbows, hips, knees, ankles—and then videotaping the actor in motion. The video images are digitized for computer extraction and calculation of the 3-D locations of the markers. The calculated results are presented in graphical form, which may be plots or stick figures. While useful, these graphics are only coarse approximations of actual human movement. If used for animation purposes, for example, they would require a great deal of rendering before they could be considered finished. For studying biomechanics, their accuracy and level of detail are limited by the relatively small number of data points from which their information has been extrapolated.

Recently, Lawrence Livermore engineers Shin-Yee Lu and Robert K. Johnson demonstrated the next step in motion imaging systems. Dispensing with reflective markers, Lu and Johnson devised a system that detects data points on a grid of parallel, closely spaced vertical lines that have been projected onto a moving object (see figure above), which is then captured at video speed. Motion information collected in this way is dense, continuous, and uniform. It can be used to produce a real-time, complex visualization of movement that is realistic enough to be pasted directly into an animation. Lu and Johnson call this system CyberSight.



(a) A vertical line grid projected onto the face of Livermore engineer Robert Johnson to capture information from closely spaced points along the lines results in (b) this CyberSight visualization.

How to Get CyberSight

The line grid projected onto a moving subject comes from a glass slide precisely etched with parallel black lines; such slides are commonly used for calibrating instrumentation optics. Other than this slide and the projector, the CyberSight system components are similar to those of other motion imaging systems. Two charge-coupled device (CCD) cameras, which are semiconductor image sensors, produce the video signals. To sense the data points, the cameras are firmly positioned a small distance apart from each other to take "snapshots" from two perspectives. Operated from 1 to 10 feet away, the cameras take the snapshots at the standard video rate of 30 frames per second. The CCD images are digitized by an image frame grabber and stored in memory boards. From there, they are transferred to a host computer for calculation and reconstruction into 3-D computer representations that can be presented as rendered images.

The sample images of a facial expression sequence in the figure on the next page are taken from CyberSight data that were reconstructed into several perspectives. Unlike a conventional photograph, the images are generated from a computer model of true dimensionality that can be manipulated, analyzed, and visualized. This feature makes CyberSight useful for biomechanical analyses. The complex information will allow computer models to calculate body surfaces and volumes, determine relationships between bones and muscles, and estimate velocity and force of movements.

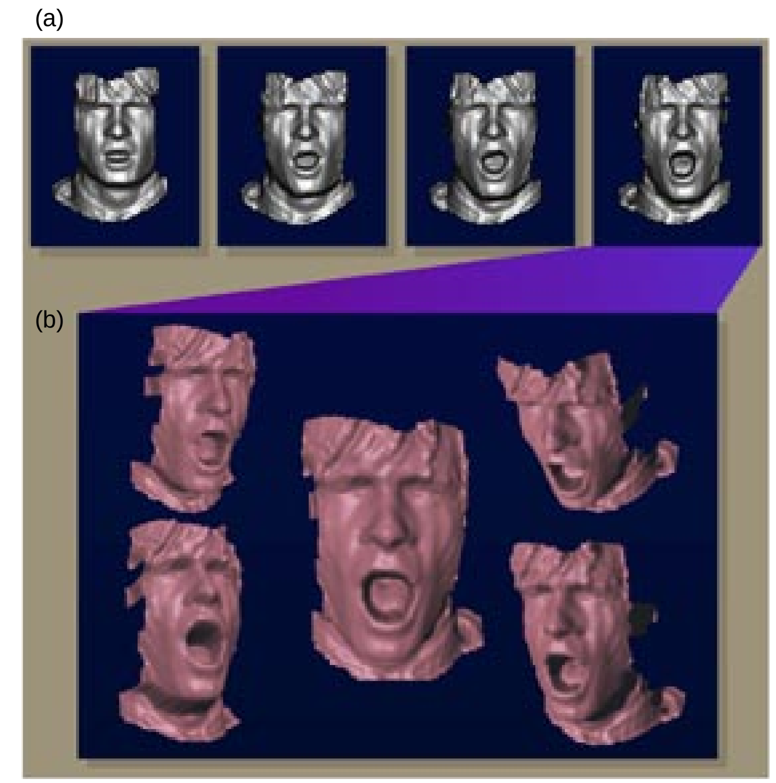
Calculating Three-Dimensional Space

By solving the problem of collecting complete, voluminous motion data, CyberSight has uncovered another problem. As

collected, the data are of two-dimensional image planes that must still be transformed into 3-D moving images. This is hardly a simple task, given that each image frame from each camera may contain as many as 250,000 data points. Thus, it is no surprise that the key component of CyberSight is its complex image-processing code.

The code transforms 2-D objects into 3-D objects by mimicking human stereo vision. When we look at an object, each eye receives a slightly different image because it sees from a slightly different angle. This angular difference provides us with depth perception. The geometric expression of depth perception has been adapted by the computer code to calculate depth, using the two views of each data point sensed by the stereo cameras. The computer calculation is based on the principle of triangulation, a measurement technique that uses two known points to derive a third value. The triangulation uses the known, left–right views of an image point, the geometry of the camera arrangement, baseline distance, and converging optical angles to establish the position of that image point in space. The figure on the next page simplifies the basis of triangulation.

Camera geometry is determined by means of a calibration process. During calibration, images are taken of reference target points with known spatial positions, and these are used to back-calculate the camera geometry and lens parameters to be used for actual videotaping.



The reconstruction of a facial sequence displayed as (a) a normal surface display at one-thirtieth of a second and (b) a rendered image from different perspectives

Matching the Left and Right "Eyes"

Before the calculations for depth can be made, the left and right views of the data points must be accurately matched. This difficult, time-consuming task requires a very high degree of computational complexity. The matching involves associating the correct left and right views of the same data point, associating them from the same image frame, and then tracking them from frame to frame so that movement reconstruction is logical. Additional complications come from changes in perspective, such as curvatures and orientation, caused by the moving object. Yet another type of problem intrudes when, on occasion, one view of a data point is eclipsed from the common view of both cameras, so not every data view has a stereo counterpart.

The computational techniques for left–right matching, like the 3-D transformation technique that imitates stereo vision, use principles based on the relationship between physical and mental processes, i.e., how stimuli lead to sensation. The computations imitate the human eye's ability to pick up intensity changes, make use of high-contrast features in an image (such as edges and intersections), and filter or "smooth" received data. They also use dynamic programming, in which small subproblems are solved. Those solutions are used to solve larger and larger subproblems until eventually the problem itself is solved. The techniques result in a code with some ability to interpret "context" in performing the left–right matches and to fill in some missing details, such as the eclipsed data views.

Building on Past Work

The work on CyberSight follows earlier robotic motion studies that Lu and Johnson performed for LLNL's in-house Laboratory Directed Research and Development project. The purpose of that work was to program robotic "hands" to handle hazardous waste. The work captured the interest of pediatric hospitals that are seeking better ways to design treatment for cerebral palsy. Their need gave Lu and Johnson

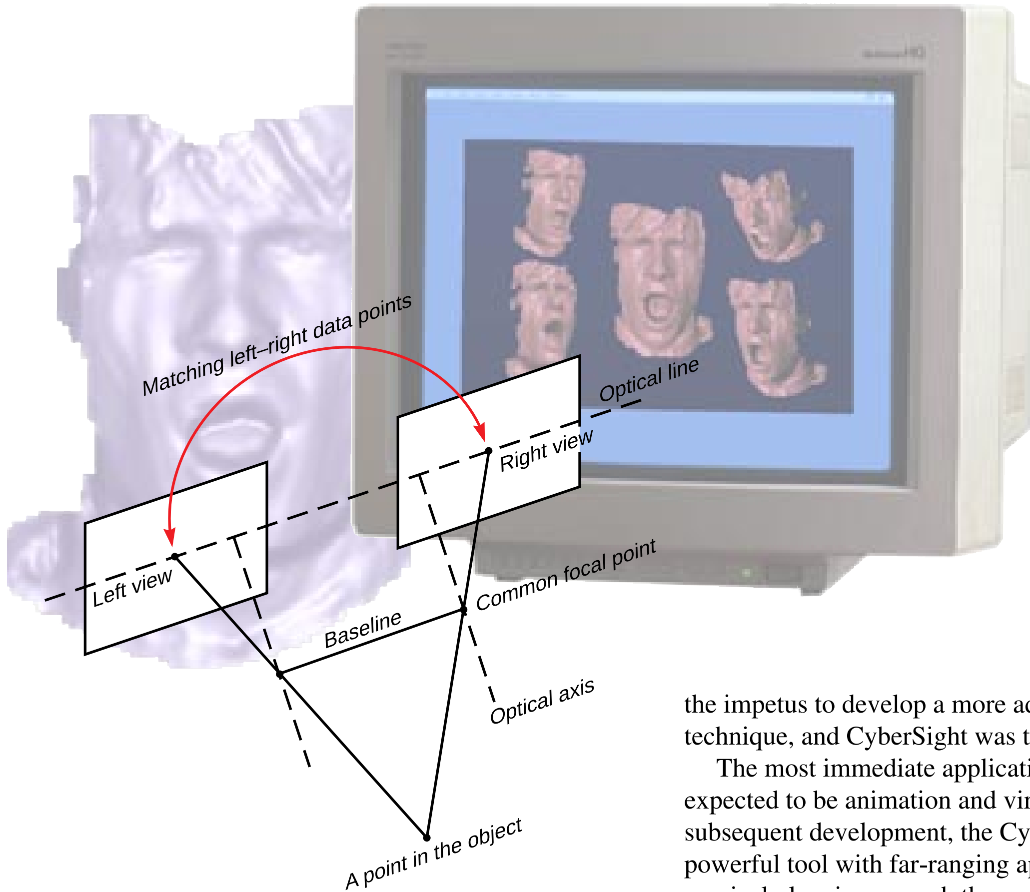


Figure 3. Triangulation is used in the CyberSight computer code to locate the data points in space.

the impetus to develop a more advanced motion imaging technique, and CyberSight was the result.

The most immediate applications for CyberSight are expected to be animation and virtual reality projects. With subsequent development, the CyberSight code will be a powerful tool with far-ranging applications from orthopedic surgical planning, speech therapy, and physical therapy to security applications such as facial recognition systems. This image-processing technology could also be used in manufacturing to provide rapid prototyping of new products and to personalize products such as prostheses, gas masks, clothes, and shoes. It has potential nonhuman-related applications as well. Surface deformations of materials could be monitored during the manufacturing process, or stress and strain analyses could be performed on materials and structures (such as vehicle air bags or the vehicle itself) to determine safety and functionality. The ingenuity of the CyberSight data collection technique, supported by its complex computer code, portends numerous and exciting future applications.

Key Words: 3-D visualization, biomechanics, image processing, motion study, movement reconstruction.

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Studying the Earth's Formation: The Multi-Anvil Press at Work

MANY things that scientists study are invisible to them. Announcements about the discovery of planets around other stars do not come because astronomers have seen the planets, although they would certainly love to. The discovery is more likely based on observations of the star's motion that indicate strong nearby gravitational forces. So it is with discoveries about the Earth's core and mantle. Because the deepest well ever drilled extends down just 12 kilometers, not even pricking the mantle, researchers have to employ indirect methods to study the Earth.

Using meteorites and seismological evidence as clues, scientists have known almost since the beginning of the century that the Earth has a solid, mostly iron, inner core and a molten outer core with a mantle and crust of rocky, silicate material. But for just as long they have been puzzled about how the core and mantle separated. The primordial planet Earth grew out of bits of gas and dust, aggregating over time into a larger, more solid body. Was there then some cataclysmic event billions of years ago that melted much of the planet, prompting the metals and silicates to separate as oil and water do? Or was the separation the result of a more gradual process, a trickling down of the denser molten metals between solid silicate mineral grains to the center of the Earth?

Recent research at Lawrence Livermore National Laboratory by geochemist William Minarik has helped to dispel the second, "trickle down," theory. Using the larger of Livermore's two multi-anvil presses to mimic the pressures and temperatures that exist deep in the Earth, he has shown that metals like those in the Earth's core could not have trickled down (see figure at right).

The materials used in the experiments were olivine, a silicate mineral that makes up much of the Earth's upper mantle, and an iron–nickel–sulfur–oxygen combination to represent the core.

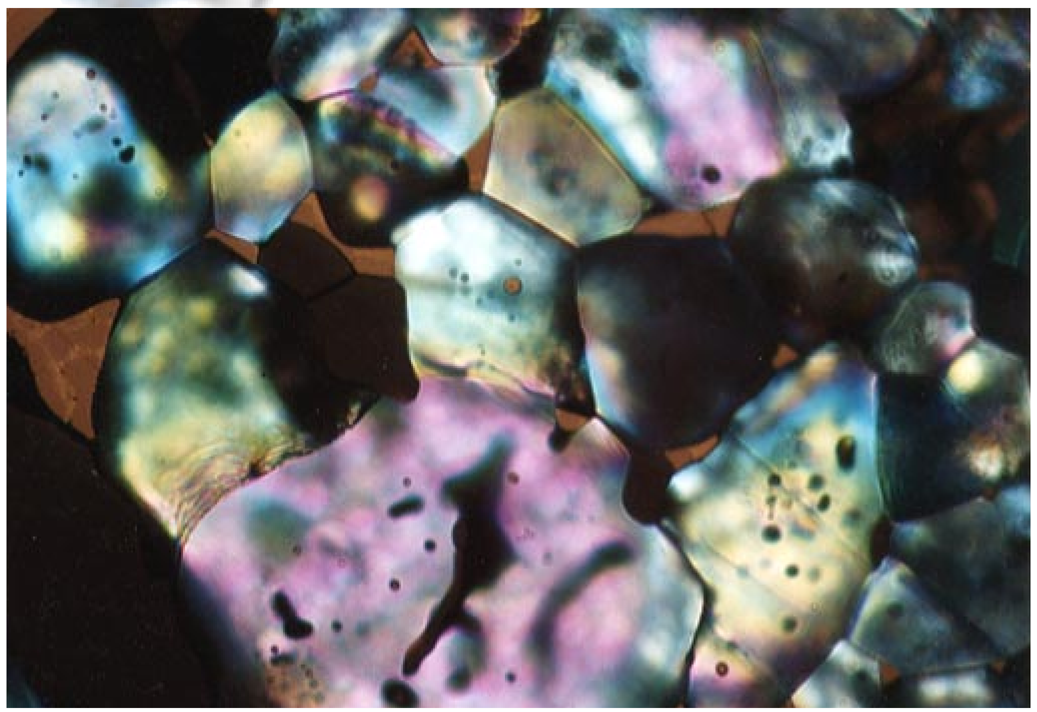
The multi-anvil press is a relatively rare research tool. Livermore's two presses have been used for a variety of material property studies, including diffusion and deformation of ceramics and metals, deep-focus earthquakes, and the high-pressure stability of mineral phases. The larger, 1,200-ton hydraulic press can produce pressures of

(a)

(b)

(c)

(a) The ceramic octahedron with the sample material inside it fits inside eight tungsten carbide cubes that in turn sit inside (b) the split cones of the multi-anvil press. (c) The closed press is also shown.



A 30-micrometer-thick slice of an experiment sample in double exposure. The field of view is about 500 micrometers. Transmitted light reveals the colorful olivine grains, while light reflected from the top shows the brown sulfides at the corners of the olivine grains. The sulfides have not wetted the edges of the olivine grains. Oxides appear black.

25 gigapascals (GPa), which is equivalent to 250,000 times the atmospheric pressure at sea level, or the pressure that occurs 700 kilometers deep in the Earth. In addition to pressing on the sample, the experiment passes an electric current through a furnace within the assembly to generate temperatures up to 2,200°C.

These experiments using the multi-anvil press generated a high pressure of 11 GPa, or 110,000 times the atmospheric pressure at sea level. This corresponds to 380 kilometers deep into the Earth, or pressures at the center of moons or asteroids 2,500 kilometers in radius (about the size of Mercury). The sample was also heated to a temperature of 1,500°C. Under those conditions, the metal melts and the olivine remains solid.

The geometry of the press is key to creating these enormous pressures. For the 11-GPa experiment, a ceramic octahedron had a 10.3-millimeter-long hole with a tiny rhenium furnace, a thermocouple to measure temperatures, and a graphite capsule containing the olivine and iron–nickel–sulfur–oxygen sample inserted in it. The octahedron rested in the center of eight 32-millimeter tungsten carbide cubes whose inside corners were truncated to accommodate the sample. (Tungsten carbide is used for the cubes, or anvils, because of its hardness, which is close to that of diamonds but at a much lower cost.) Tiny ceramic gaskets were placed at the edges of the carbide cubes to contain the pressure. This assembly of an inner octahedron and eight carbide anvil cubes was put in the press's split-cone, steel buckets as shown in the figure on p. 21. In several stages, the steel buckets pushed on the carbide cubic anvils, which pushed on the octahedral volume inside.

The multi-anvil press is not Livermore's only device for studying the behavior of the Earth's innards, but in many ways it is the best for this type of study. The diamond-anvil cell can produce 100-GPa pressures, comparable to the pressures at the center of the Earth (see *Science & Technology Review*, March 1996). But it can accommodate only a 20-micrometer sample, too small for much post-experiment evaluation. With the piston-cylinder press, the sample volume is about 500 millimeters^3, but it has only a 4-GPa pressure capability, which is comparable to a depth of just 120 kilometers. The multi-anvil press is in the middle, providing pressures useful for studies of this type and accommodating a sample large enough for evaluation after the experiment.

In Minarik's experiments, the press took about 4 hours to bring the samples to full pressure, after which the samples were heated for periods ranging from 4 to 24 hours. During this time, the porosity of the sample collapsed, and the stable microstructure developed. Then the unit was cooled down and allowed to decompress for about 12 hours. During this process, the graphite capsule turned to diamond, which must be ground off before the sample could be sliced and polished for evaluation.

Despite being molten and much denser than the olivine, the metallic melt showed no signs of separating and draining to the bottom of the capsule. For the molten metal to drip down along the silicate grain edges, it has to be able to wet the edges. But in none of the experiments did wetting occur.[1] Rather, the iron–nickel mixture beaded up at the corners of the silicate grains like water does on a waxed car, as shown in the figure on p. 22.

Livermore's findings agree with similar, lower-pressure studies that have melted meteorites and iron–nickel–sulfur–oxygen mixtures and failed to wet the silicate minerals. Together, these experiments indicate that much higher temperatures were required to separate the Earth's core and mantle—temperatures high enough to melt most of the Earth.

All of these data lend credence to the theory that the young, growing Earth was repeatedly bombarded by large planetoids, with some of these collisions generating temperatures high enough to form a magma ocean from which drops of dense molten metal separated. The largest collision may have been when a large celestial body, about the size of Mars, collided with Earth nearly 4.5 billion years ago, melting most of it and causing the core and mantle to separate. The leading theory today for the Moon's formation postulates that some material from that collision was ejected into orbit and condensed into the Earth's Moon.

Livermore scientists have long studied material properties and the effects of high temperatures and pressures. Their work has resulted in some mighty big bangs but none as large as the ones Minarik has postulated.

"We plan to look next at the geochemical aspects of this project, the partitioning of trace elements between molten metal and silicates at the same high temperatures and pressures," says Minarik. "There are many scientists in this country and elsewhere studying the formation of the Earth, and all of us are in the same boat. With all of the direct evidence of the Earth's formation buried far beneath our feet, these laboratory experiments are our only way to recreate what might have happened."

Key Words: Earth core formation, multi-anvil press.

References

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Patents and Awards

Each month in this space we report on the patents issued to and/or the awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patents

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
James L. Kaschmitter	**Three-Dimensional Amorphous Silicon/Microcrystalline Silicon Solar Cells** U.S. Patent 5,538,564 July 23, 1996	Solar cells that use deep (high-aspect-ratio) p and n contacts to create high electric fields within the carrier collection volume material of the cell. The deep contacts are fabricated using repetitive pulsed laser doping so as to create the high-aspect p and n contacts. The provision of the deep contacts that penetrate the electric field deep into the material where the high strength of the field can collect many of the carriers results in a high-efficiency solar cell.
Gerald W. Coutts John F. Bushman Terry W. Alger	**Mass Spectrometer Vacuum Housing and Pumping System** U.S. Patent 5,539,204 July 23, 1996	A vacuum housing that is composed of cleaned and welded stainless-steel tube components and includes flanges sealed with metal gaskets. The housing is broadly composed of two interconnected tubular sections (each section having a flange at the outer end and at the main body section). The vacuum pumps require simple and minimal electrical controls and use minimal electrical power. These attributes allow packaging into a small, lightweight volume that will operate with minimal power.
Charles L. Bennett	**Method for Determining and Displaying the Spatial Distribution of a Spectral Pattern of Received Light** U.S. Patent 5,539,518 July 23, 1996	An imaging Fourier transform spectrometer employing an interferometer coupled to a digital framing camera. Output from the digital framing camera is provided to a computer that, by manipulation of that data, can display a two-dimensional representation of measured spectra and/or numerical data pertaining to those spectra. The digital framing camera is optically and electrically coupled to the output of the interferometer such that an interferogram is recorded at precise intervals in synchrony with the movement of the moving mirror of the interferometer.
William F. Krupke Ralph H. Page Laura D. DeLoach Stephen A. Payne	**Transition-Metal-Doped Sulfide, Selenide, and Telluride Laser Crystal and Lasers** U.S. Patent 5,541,948 July 30, 1996	A new class of solid-state laser crystals and lasers that are formed of materials that have fourfold coordinated substitutional sites. The host crystals include II-VI compounds that are doped with a transition metal laser ion (e.g., chromium, cobalt, or iron). Important aspects of these laser materials are the tetrahedral site symmetry of the host crystal, low excited-state absorption losses, high luminescence efficiency, and the d4 and d6 electronic configurations of the transition metal ions.
Ravindra S. Upadhye Francis T. Wang	**Clean Process to Destroy Arsenic-Containing Organic Compounds with Recovery of Arsenic** U.S. Patent 5,545,800 August 13, 1996	A process using a reducing agent to decompose an organic compound containing arsenic. The reducing agents may include alkali metals, alkaline earth metals, hydrides, and hydrogen gas. In the case of a pure metal reducing agent, an intermediate metal arsenide is formed that may be acidified to form an arsenic-containing gas, such as arsine. The arsine gas is then reduced to pure arsenic by a thermal or chemical process. This reduction process avoids the costly separation or disposal of arsenic oxide.
Don E. Fischer Don Walmsley P. Derek Wapman	**Crimp Sealing of Tubes Flush With or Below a Fixed Surface** U.S. Patent 5,546,783 August 20, 1996	An apparatus used when a ductile metal tube and valve assembly are attached to a pressure vessel that has a fixed surface around the base of the tube at the pressure vessel. A flat anvil is placed against the tube, die guides are placed against the tube on a side opposite the anvil, and a pinch-off die is inserted into the die guides against the tube. Adequate clearance for inserting the die and anvil around the tube is needed below the fixed surface. The anvil must be flat, so that, after crimping, it may be removed without deforming the crimped tubes.
Malcolm Caplan Clifford C. Shang	**Vacuum-Barrier Window for Wide-Bandwidth High-Power Microwave Transmission** U.S. Patent 5,548,257 August 20, 1996	A vacuum output window that comprises a planar dielectric material with identical systems of parallel ridges and valleys formed in opposite surfaces. The valleys in each surface neck together along parallel lines in the bulk of the dielectric. Liquid-coolant conduits are disposed linearly along such lines of necking and have water or liquid nitrogen pumped to remove heat. The ridges focus the incident energy in ribbons that squeeze between the liquid-coolant conduits without significant losses over very broad bands of the radio spectrum.

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Gary E. Sommargren	**Phase Shifting Diffraction Interferometer** U.S. Patent 5,548,403 August 20, 1996	An interferometer having the capability of measuring optical elements and systems with an accuracy of ¬/1,000, where ¬ is the wavelength of visible light. This interferometer uses an essentially perfect spherical reference wavefront generated by the fundamental process of diffraction. The interferometer is adjustable to give unity fringe visibility, which maximizes the signal to noise and has the means to introduce a controlled, prescribed relative phase shift between the reference wavefront and the wavefront from the optics under test.
William J. Benett Raymond J. Beach Dino R. Ciarlo	**Monolithic Microchannel Heatsink** U.S. Patent 5,548,605 August 20, 1996	A silicon wafer that has slots sawed in it that allow diode laser bars to be mounted (soldered) in contact with the silicon. Microchannels are etched into the back of the wafer to provide cooling of the diode bars. The channels are rotated from an angle perpendicular to the diode bars, allowing increased penetration between the mounted diode bars. Low thermal resistance of heatsinks allow high average power operation of two-dimensional laser diode arrays.
Troy W. Barbee, Jr. Timothy Weihs	**Method for Fabricating an Ignitable Heterogeneous Stratified Metal Structure** U.S. Patent 5,547,715 August 20, 1996	Method for fabricating a multilayer structure with selectable features: propagating reaction front velocity V, reaction initiation temperature attained by application of external energy, and amount of energy delivered by a reaction of alternating unreacted layers of the multilayer structure. Because V is selectable and controllable, a variety of different applications for the multilayer structures are possible, including use as ignitors, in joining applications, in fabrication of new materials such as smart materials, and in medical applications and devices.
Karla Hagans Leon Berzins Joseph Galkowski Rita Seng	**Self-Tuning Method for Monitoring the Density of a Gas Vapor Component Using a Tunable Laser** U.S. Patent 5,550,636 August 27, 1996	A method using a tunable laser for determining the density of a gas vapor component that absorbs light at an expected maximum frequency. A laser is tuned to transmit a laser source beam at a local maximum absorptance frequency of the component by transmitting at last one laser source beam through at predetermined path of gas vapor. The frequency of the laser source beam is swept through a frequency range, including the expected maximum absorptance frequency.

Awards

Laboratory scientists **Bruce Hammel** and **Laurance Suter** have been elected fellows by the American Physical Society. Their election brings to 30 the number of APS fellowships earned by the Laboratory's Inertial Confinement Fusion Program in the last 20 years.

The citation on Hammel's certificate reads "for measurements and understanding of x-ray-driven hydrodynamic instabilities and x-ray drive asymmetry." Hammel is currently head of experimental research within the ICF Program and is responsible for experiments on the Nova laser.

Suter was cited for "pioneering work and leadership in the design, modeling, and analysis of experiments using laser-heated hohlraums that quantify and control x-ray drive, symmetry, and pulse-shaped implosions." He is currently the leader of the Hohlraum Group in the Theory and Target Design (X) Division of the Laser Programs Directorate and is working on a new type of source for producing x rays with high-powered lasers for the future National Ignition Facility.

Sixteen organizations were awarded the 1996 DOE Energy Quality Awards in October, including Livermore's **Business Services Department**, in recognition of substantial achievement in quality management.

"These award winners have demonstrated excellence in 'reinventing government' in support of the President's National Performance Review principles: putting customers first, cutting red tape, empowering employees, and getting back to basics," said DOE Secretary Hazel O'Leary.

Crossing the Petawatt Threshold

A revolutionary new laser called the Petawatt, developed by Lawrence Livermore researchers after an intensive three-year development effort, has produced more than 1,000 trillion (“peta”) watts of power, a world record. By crossing the petawatt threshold, the extraordinarily powerful laser heralds a new age in laser research. Lasers that provide a petawatt of power or more in a picosecond may make it possible to achieve fusion using significantly less energy than currently envisioned, through a novel Livermore concept called “fast ignition.” The petawatt laser will also enable researchers to study the fundamental properties of matter, thereby aiding the Department of Energy’s Stockpile Stewardship efforts and opening entirely new physical regimes to study. The technology developed for the Petawatt has also provided several spinoff technologies, including a new approach to laser material processing.

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High Explosives in Stockpile Surveillance Indicate Constancy

Although stockpile evaluation is not new, methods and tests have undergone marked changes since the program’s inception almost four decades ago. Today Lawrence Livermore, Los Alamos, and Sandia National Laboratories are responsible for the extensive and rigorous tests to evaluate the portions and components of the stockpile weapons that each has designed. An overview of Livermore high-explosives tests of components in nuclear stockpile weapons illustrates the degree of assurance that the laboratories work toward. Evaluation includes tests for changes in physical properties, mechanical properties with tensile and compression tests, and performance with pin-dome, “snowball”, and aging tests. Looking toward the future, the program is working to improve predictive capabilities so that weapons designed at Livermore can safely be stored and work exactly as intended throughout their stockpile life.

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